IDENTIFICATION OF ROCKBURSTS AND OTHER MINING EVENTS USING REGIONAL SIGNALS AT INTERNATIONAL MONITORING SYSTEM STATIONS

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ABSTRACT

Rockbursts present some unique challenges for seismic event identification at low-magnitude monitoring thresholds. Teleseismic discriminants, including traditional determination of focal depth and M_S-versus-m_b, are not likely to work for these types of sources. Since many rockbursts are small, their identification depends heavily on observations from a few regional stations. This research program is designed to identify rockburst regions with respect to their significance to nuclear test monitoring, assess the capability of prototype International Data Centre (PIDC)/IDC screening procedures for application in rockburst regions worldwide, and determine ways to improve event identification for such mining regions.

During the time period from 1995 to 2000, more than 1100 events were reported in the Reviewed Event Bulletin (REB) within 50 km of 43 historical rockburst sites. Most of these had magnitudes in the range 3 to 4. No REB events were located in proximity to 61 other rockburst sites, although small events (below the REB threshold) may be occurring in those areas. Waveform data from regional International Monitoring System (IMS) stations for Reviewed Event Bulletin (REB) events in each rockburst area are being collected and analyzed. For many of these events, we have been able to establish better ground truth information using local and regional seismic bulletins or, in some cases, information reported from the mines or other agencies; and we have been seeking to establish ground truth information for events in more mining areas. This ground truth information is valuable for event location (as some of the small events are significantly mislocated) and in some cases for identifying event source mechanisms, which permits better understanding of signal variability.

We have been carefully analyzing the regional signal characteristics for REB events from several of the more active rockburst areas. We have found differences and variability in the regional signals between events as well as between source types. Although the evidence seems to indicate that on average L_g/P and S/P ratios are larger, particularly at high frequencies, for earthquakes and rockbursts than for underground nuclear tests, there appears to be considerable variability between events and some overlap. In particular, we have found regional signals from underground nuclear explosions which have L_g/P_g and L_g/P_n ratios at high frequencies (4-6 Hz and 6-8 Hz bands) larger than similar ratios for rockbursts and mineblasts and as large as those for some earthquakes, under similar propagation conditions. This could lead to identification mistakes or missed events if these events were screened out. This problem may be solved by more careful analyses as well as alternative identification methods. We are continuing to investigate alternative regional discriminant measures (including regional M_S/m_b, SP/LP, L_g spectral ratios, signal complexity, P-wave first motion) to supplement current event screening and source identification methods for mining events. Our improved ground truth data for rockbursts and other seismic sources in their vicinity have also revealed some potential questions related to identification of non-nuclear blasts. Proposed IDC regional screening procedures based on high-frequency P/L_g ratios screen out some known mineblasts. While this result may be reasonable in principle, it is indicative of a range in behavior from chemical blasts, which is related to source mechanism differences, and could be a cause for false alarms, missed events, or potential evasion. A broader range of regional discriminants may be useful for more precise identification of some of these chemical blasts.

KEY WORDS: rockburst, mining, seismic, regional, identification, discrimination, screening, IMS, IDC

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OBJECTIVE

Rockbursts and other mining sources present unique problems for discriminating and screening seismic events. Shallow focal depths and anomalous source mechanisms from these mining events often produce seismic signals similar to those of underground nuclear explosion tests. Because of their small magnitudes, the strongest and most distinctive signals for these events tend to be those recorded at regional stations. The goal of this research project has been to analyze the results of PIDC/IDC screening procedures in mining areas with a known history of rockbursts and to develop better discrimination techniques using the signals observed at regional IMS stations for seismic source screening.

RESEARCH ACCOMPLISHED

Mining-induced seismic activity occurs in mining regions all over the world. During prior stages of this research program, we identified 104 historical rockburst areas worldwide (cf. Figure 1), although other mining areas may also be subject to such events. We collected parametric information and IMS station waveforms for 1108 events reported by the PIDC/IDC during a five year monitoring period (1995-2000) for 43 of these areas; activity in the other areas appears to be absent or below the PIDC/IDC detection threshold. We also analyzed the PIDC/IDC screening results for events from the vicinity (within 50 km) of each of the known rockburst areas. Screening procedures based on teleseismic discriminants (including M_S-versus-m_b and focal depth estimates) are generally found to be ineffective for these mining areas, mainly because the events have magnitudes below the screening threshold or because the data are insufficient to form the signal measurements needed to determine the screening parameters. However, we also found indications that LP excitation (and hence M_S) is often low for rockbursts, which makes them appear explosion-like with respect to M_S-versus-m_b; and their focal depths are in the same range as underground nuclear tests. Therefore, screening methods based on alternative measures, which discriminate other kinds of source differences, and in particular on regional discriminants are needed for these mining events. In addition to P/L_g ratios at high frequencies, which are currently proposed for use by the PIDC/IDC in event screening, other potential regional discriminants that may prove useful include regional P-wave complexity, P-wave first motions, L_g spectral ratios, and a regional version of M_S-versus-m_b.

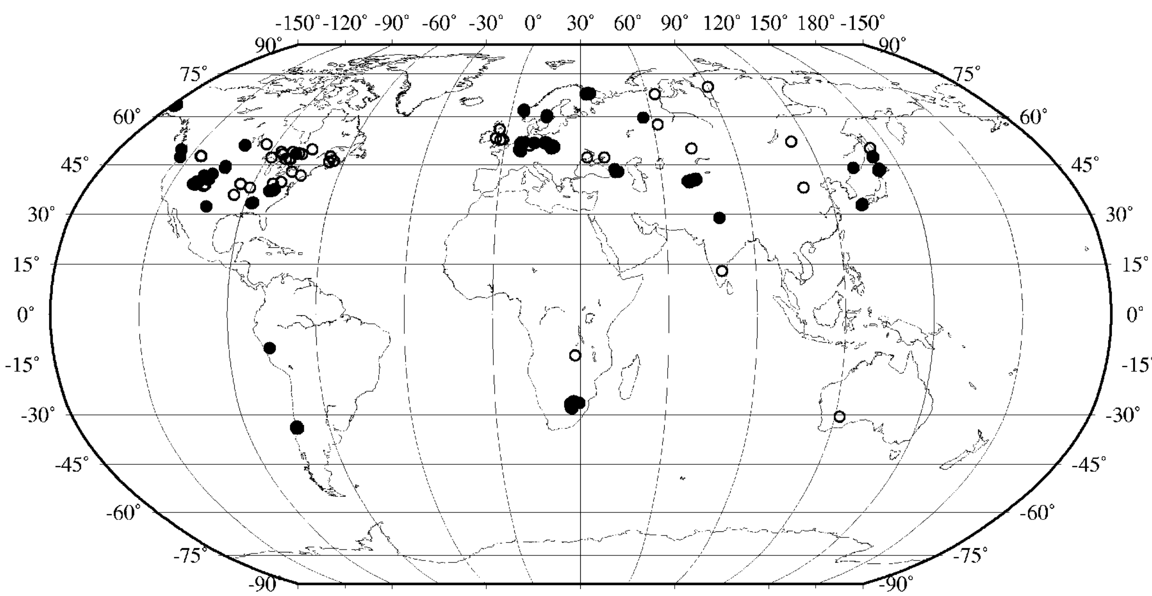


Figure 1. Locations of 1108 events in 1995 - Present PIDC REB database that are within 50 km of 104 historical rockburst sites. Solid circles indicate sites with at least one REB event, and open circles show sites with none.

We have been looking closely at the signals recorded at regional IMS stations from seismic events in rockburst areas to identify characteristics which can be used for source discrimination. These events include rockbursts and mine collapses, but also nearby mining explosions and earthquakes. For comparison, we have also selected several older underground nuclear explosion tests recorded at regional distances. Unfortunately, the latter observations are not available at regional IMS stations, because very few nuclear tests have occurred while the IMS network has been operational. However, many historical nuclear explosions have been recorded at high-quality digital stations [e.g. the Lawrence Livermore National Laboratory (LLNL) seismic network]; and these provide the best basis for comparison with signal characteristics at similar regional distances for IMS stations.

In our initial studies of signal characteristics, we looked at more general properties of events from several of the more active rockburst areas. These included coal and copper mining areas in Poland, several deep gold mining areas in South Africa, and coal mining areas in the Kola peninsula of Russia. More recently, we have focused on events with better ground truth including mining areas in the western U.S. and Europe. By looking at events with better ground truth and analyzing more carefully potential discriminant measures, we hope to develop better understanding of the variability between source types and the regional signals they produce. In some of these areas, different types of seismic sources (viz. mineblasts, rockbursts, and earthquakes) may occur in the same mining area. However, it is sometimes difficult to identify events with regional signals above background noise for rockbursts and other source types that have similar propagation paths to regional IMS stations. This is certainly the case for comparable nuclear test sources, as described above. One option is to attempt to correct regional signal amplitude measurements for propagation differences (cf. Bennett et al., 1997; Fisk et al., 2000), so as to isolate source effects; however, such corrections are expected to have strong regional dependence and may, therefore, lead to results which mix propagation effects with source differences, if the propagation corrections are inaccurate. In this study, we have tried to follow an alternative approach using more direct comparisons between regional signals from different sources at similar observation distances and, where possible, with propagation paths in the same or similar tectonic regions.

The region where this approach seems most appropriate is the western U.S. Within the western U.S. the most active rockburst areas (cf. Figure 2) are in the Wasatch Plateau-Book Cliffs region of southern Utah, where the events are generated in association with underground coal mining. Another area of rockbursts occurs in association with trona mining in southwestern Wyoming, where infrequent mine collapses have sometimes been quite large. Finally, there are some other scattered areas (viz. in northern Idaho, western Washington, and southern New Mexico) where small mining-induced events occur but are not usually detected at regional IMS stations. Most mines utilize chemical explosions to some degree in normal operations; however, such mineblasts are often small, and only a relatively small number of these events (usually strip-mine blasts) are large enough to be detected at IMS stations. Figure 2 shows several mineblasts in the western U.S. that were detected and located by the PIDC/IDC in southwestern and eastern Wyoming, southern Montana, northeastern Colorado, and Utah. Ground truth from United States Geological Survey (USGS) mining reports (cf. Dewey and Leeds, 2000) and regional seismic bulletins (e.g. University of Utah) can often provide more precise locations. The ground truth locations often show tighter clustering around the known mines; and, in some cases, indicate significant mislocation. Underground nuclear explosions in southern Nevada have in some cases been recorded at seismic stations common to the PIDC/IDC, and these events recorded at similar regional distances provide an excellent basis for comparison to other source types and regional discriminant analysis. Finally, there are numerous earthquakes in the region, including many with ground truth from regional seismic bulletins; and these too have available waveform data from regional IMS stations during this time period. In Figure 2 we show several earthquakes in proximity to the Utah rockburst area, and others are located adjacent to the Nevada Test Site which provide good regional signals for use in these discrimination analyses.

Direct comparisons of regional signal characteristics for identifying screening discriminants are somewhat more difficult for ground truth events from Europe. Although we still have rockbursts, chemical explosions, and earthquakes recorded at some regional European IMS stations at similar distances, the propagation paths are sometimes more complex, particularly at larger distances; and there are no nuclear explosion tests which can provide comparisons for this or similar tectonic regions. Figure 3 shows a comparison of event locations determined by the PIDC/IDC for selected rockbursts, earthquakes, and

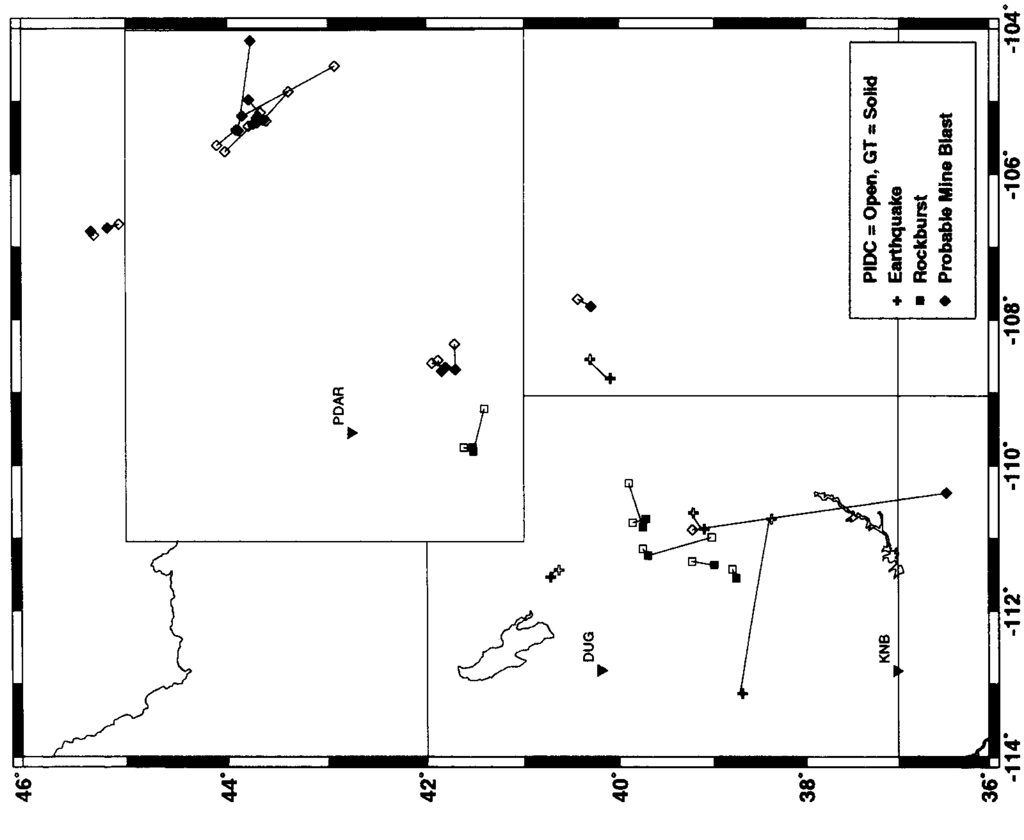


Figure 2. Comparison of PIDC and ground truth (GT) locations of selected rockbursts, explosions and earthquakes recorded at the IMS regional stations in the western U.S.

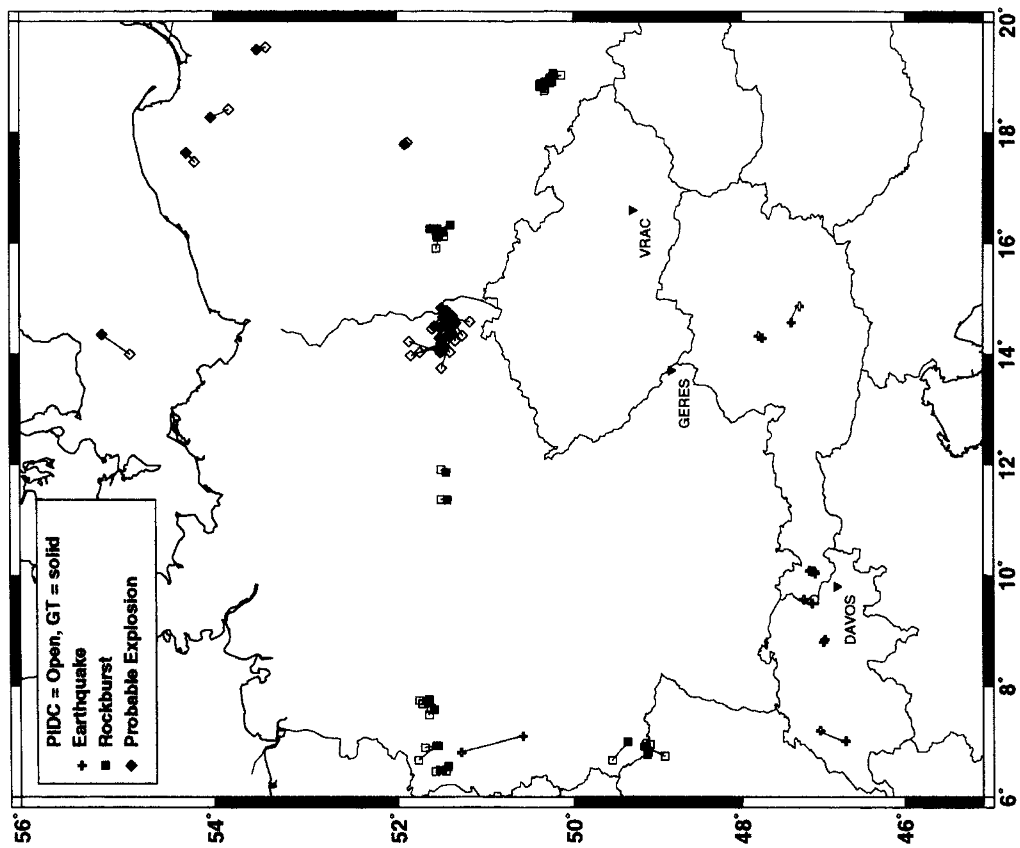


Figure 3. Comparison of PIDC and ground truth (GT) locations of selected rockbursts, explosions and earthquakes recorded at the IMS regional stations in Europe.

chemical explosions in Europe. The most active areas for rockbursts are shown by the two event clusters in Poland located in the copper mining area near Lubin (to the west) and in the Upper Silesia coal mines (to the east). There have also been infrequent, but large, mine collapses in eastern Germany near Völkerhausen and frequent, but small, rockbursts in the Ruhr valley coal mines of western Germany. Areas of mineblasts, including many reported in the PIDC/IDC REB, are known in eastern Germany; and several other chemical blasts with good ground truth are known in Poland. There are also several sources of known natural earthquakes scattered throughout Europe, with some of the larger events located in the Alps. Coverage by local seismic networks throughout Europe is good; and we have been using information compiled by the Federal Institute of Geosciences and Natural Resources in Hanover, Germany and by the Institute of Geophysics of the Polish Academy of Sciences to establish better ground truth for many of the REB events. In Figure 3 we show the location differences between the REB and local network ground truth; the differences are generally small with largest differences occurring for earthquakes. In general, the ground truth locations tend to show tighter clustering around known mines.

Over the past year, we have been looking more closely at the regional signals at IMS and similar high-quality stations from several of these events with better ground truth. As noted above, P/S or P/L_g amplitude ratios based on observations at regional stations have been identified as one of the most promising regional discriminant measures for use in event screening (cf. Taylor et al., 1988; Bennett et al., 1992; Fisk et al., 1999). As we have shown in prior reports (cf. Bennett et al., 1996, 1999, 2000), there also appear to be systematic differences in L_g/P ratios between rockbursts and underground nuclear tests; and the differences are often most apparent within limited frequency bands and most notably at higher frequencies. We have shown in prior studies that L_g/P_g ratios at IMS stations are, on average, larger in high-frequency bands for rockbursts and earthquakes than for underground nuclear explosions and mineblasts. However, we also found some evidence of scatter for individual events; and we have, therefore, been looking at alternative regional discriminants for problem events.

Figure 4 shows the regional signals at ELK from different source types in the western U.S., including a Utah rockburst, a Utah earthquake, the GORBEA nuclear test, and a southern Nevada earthquake, all recorded at similar distances (between about 400 and 435 km). We show the bandpass filtered signals for two passbands (viz. 2-4 Hz at the top and 6-8 Hz at the bottom). As noted in the preceding paragraph, GORBEA is one explosion which appeared to produce an anomalous result when analyzing the L_g/P_g ratio at high frequencies; and, in fact, we see in Figure 4 that the L_g/P_g ratios for GORBEA are greater than 1.0 (unlike the average behavior for NTS explosions for which the ratios are smaller than 1.0). In Figure 4 the biggest differences appear to be in the more energetic P_n signal for GORBEA, which is most notable in the higher frequency band. So, it seems likely that more careful analyses of the regional P_n may, in this case, be diagnostic; however, it is also noteworthy that P_n for some of the other source types has relatively low signal-to-noise, particularly in higher frequency bands. Therefore, L_g/P_n ratios may present a different kind of problem for application to event screening.

Considering the relative strength of P_n for the nuclear explosion in Figure 4 and prior studies suggesting P first motion (e.g. Pomeroy et al., 1982) or regional P-wave complexity (e.g. Blandford, 1993) as potential discriminants, we have looked more closely at the initial P signals recorded at regional IMS stations for some of these events. Blandford found that mining explosions in Scandinavia, when high-pass filtered (with low-frequency corners at 1 Hz and 2 Hz), produced impulsive initial P over a distance range from 200 to 720 km; while earthquakes from the same region and in the same distance range with the same processing produced emergent P arrivals. We have attempted to apply similar signal processing to the P_n signals from the same western U.S. events (i.e. Utah rockburst, two earthquakes, and GORBEA nuclear test) as those shown above in Figure 4. At the top of Figure 5, we show the initial P signals at station ELK after high-pass filtering with the low-frequency corner at 1 Hz; and at the bottom, alternative processing after high-pass filtering with the corner at 4 Hz. Several observations can be made from these records. First, the impulsive nature of the initial P is difficult to discern in these records; although the initial P for the GORBEA nuclear explosion has higher signal-to-noise than for the other source types, the regional P for GORBEA and the other events as well appears to show a gradual build up over the first several seconds after onset. Furthermore, while the P-wave first motion for GORBEA appears to be clearly compressional, first motions for all the other events are ambiguous. There are no unambiguous dilatational P first motions

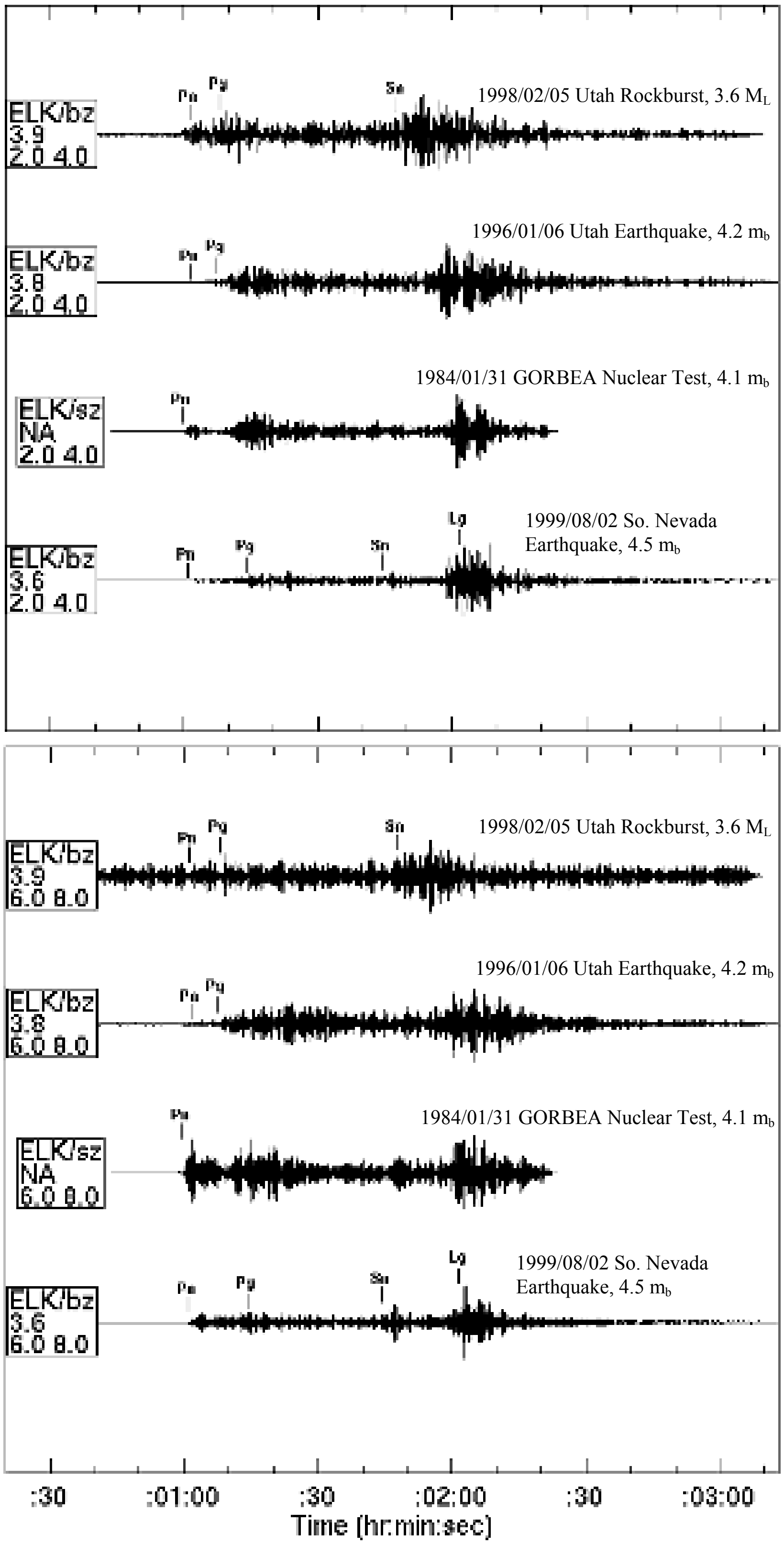


Figure 4. Comparison of regional signals at ELK from Utah rockburst, Utah earthquake, NTS nuclear explosion, and southern Nevada earthquake at similar distances (400 - 435 km) in two passbands: 2-4 Hz (top) and 6-8 Hz (bottom).

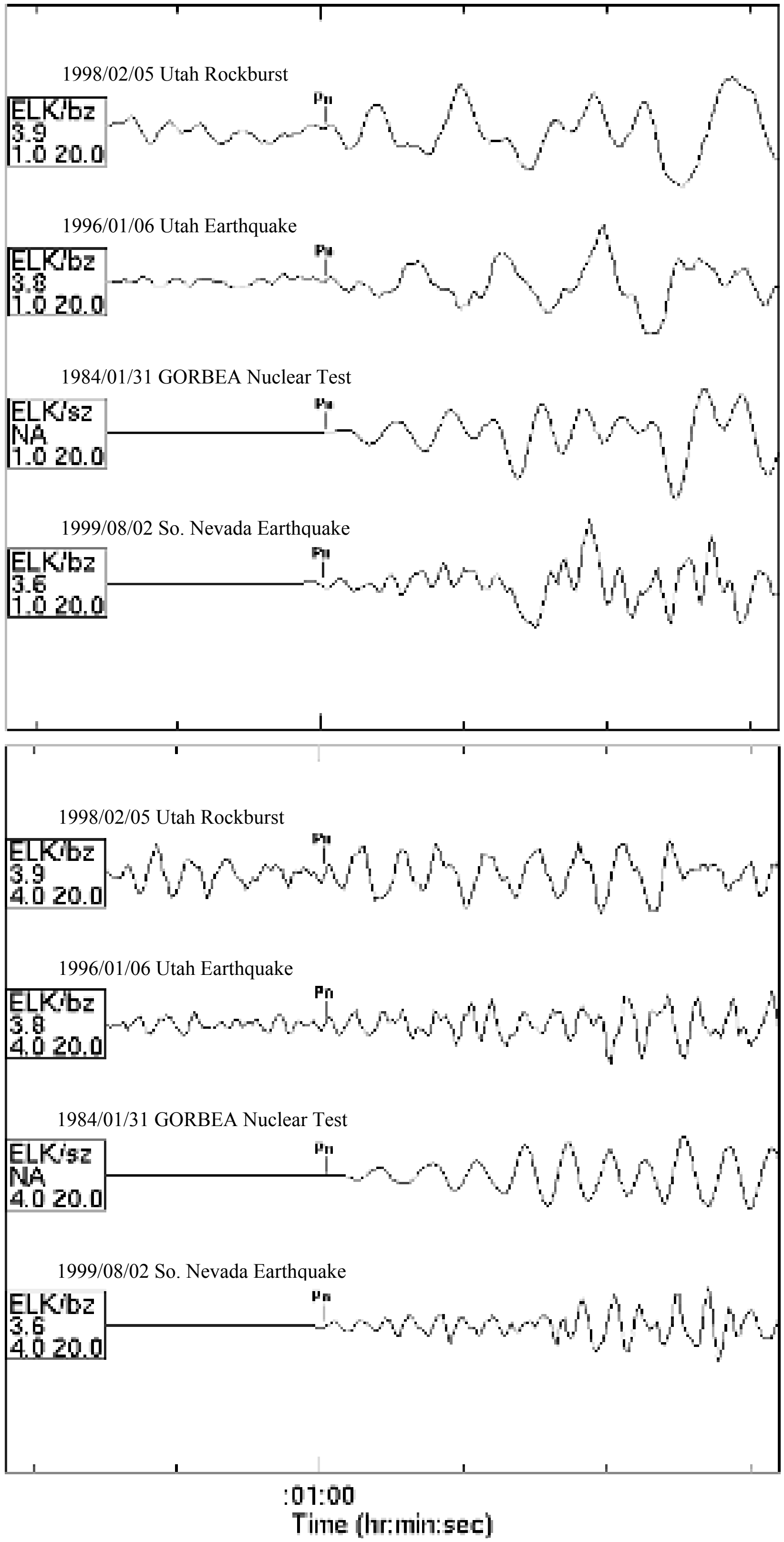


Figure 5. Comparison of initial regional P signals at ELK from Utah rockburst, Utah earthquake, NTS nuclear explosion, and southern Nevada earthquake at similar distances (400 - 435 km) for two highpass filters: 1 Hz corner (top) and 4 Hz corner (bottom).

which might allow discrimination or screening out of the remaining three events. This result does not look promising for screening events in this magnitude ($m_b \leq 4$) and distance ($R \geq 400$ km) range for tectonically active propagation environments like the western U.S. based on P first motions. We also see little evidence of greater complexity in the initial regional P signals for the rockburst and earthquakes compared to the nuclear explosion, although we are continuing to look at these and other events using systematic measures in different frequency bands which might permit some discrimination.

Another regional discriminant which we have been investigating for screening rockbursts and other mining events is relative long period (LP) or M_S excitation. Although our past studies (cf. Bennett et al., 1996) have suggested relatively weak M_S from rockbursts, the majority of mining-induced seismic events are too small to produce measurable LP Rayleigh waves at teleseismic stations; so we lack reliable measurement samples on which to base M_S-versus-m_b screening for rockbursts. We have been continuing to look for observations of LP Rayleigh wave signals at regional distances from rockbursts and other source types which may be useful for screening or determining potential screening problems. Figure 6 shows LP signals for the same four western U.S. events at station ELK after bandpass filtering for the passband 0.03 to 0.10 Hz. In this distance range the two earthquakes appear to have clear LP Rayleigh signals with dominant periods of about 12 seconds. There appears to be little evidence of LP Rayleigh in the corresponding rockburst record; and, unfortunately, the available nuclear explosion signal is cutoff prior to the expected LP Rayleigh wave arrival time. Similar processing of several other Utah rockbursts also showed no indication of LP Rayleigh signals above background noise. However, we have seen LP Rayleigh waves in regional records from some of the southwestern Wyoming mine collapse events, although the LP signals again appear weak relative to m_b. We are continuing to look into better procedures to extract M_S and determine M_S-versus-m_b screening from regional signals for these small events.

In addition to western U.S., we have been looking more closely at the same kinds of regional IMS station measurements from European events with good ground truth. Figure 7 shows a comparison of bandpass filter analyses of regional signals at GERES for an eastern Germany mine collapse (at the top) and an eastern Germany mineblast (bottom). The figure shows roughly similar L_g/P ratios in most frequency

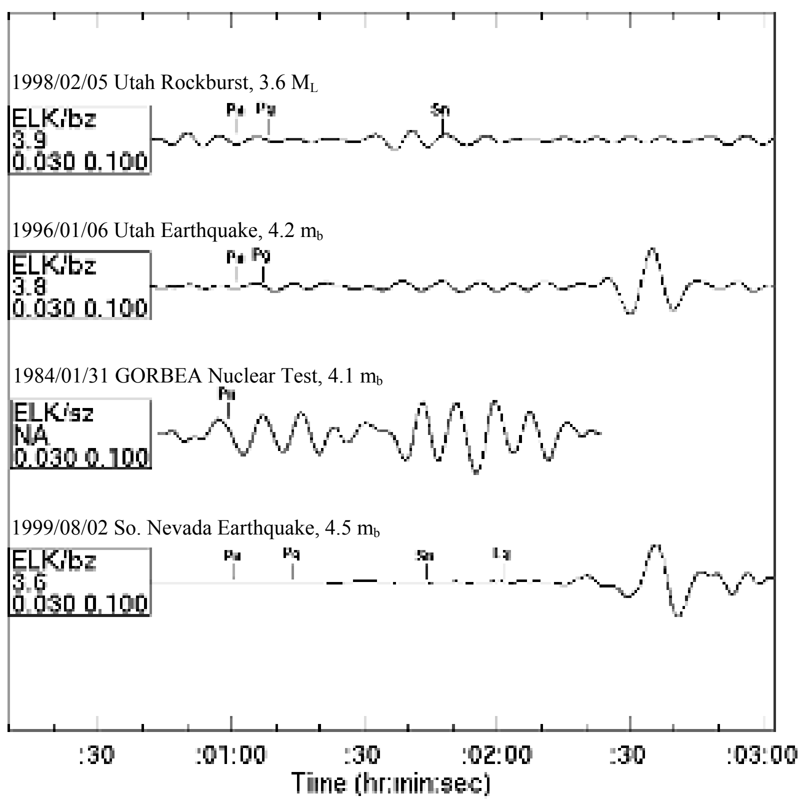
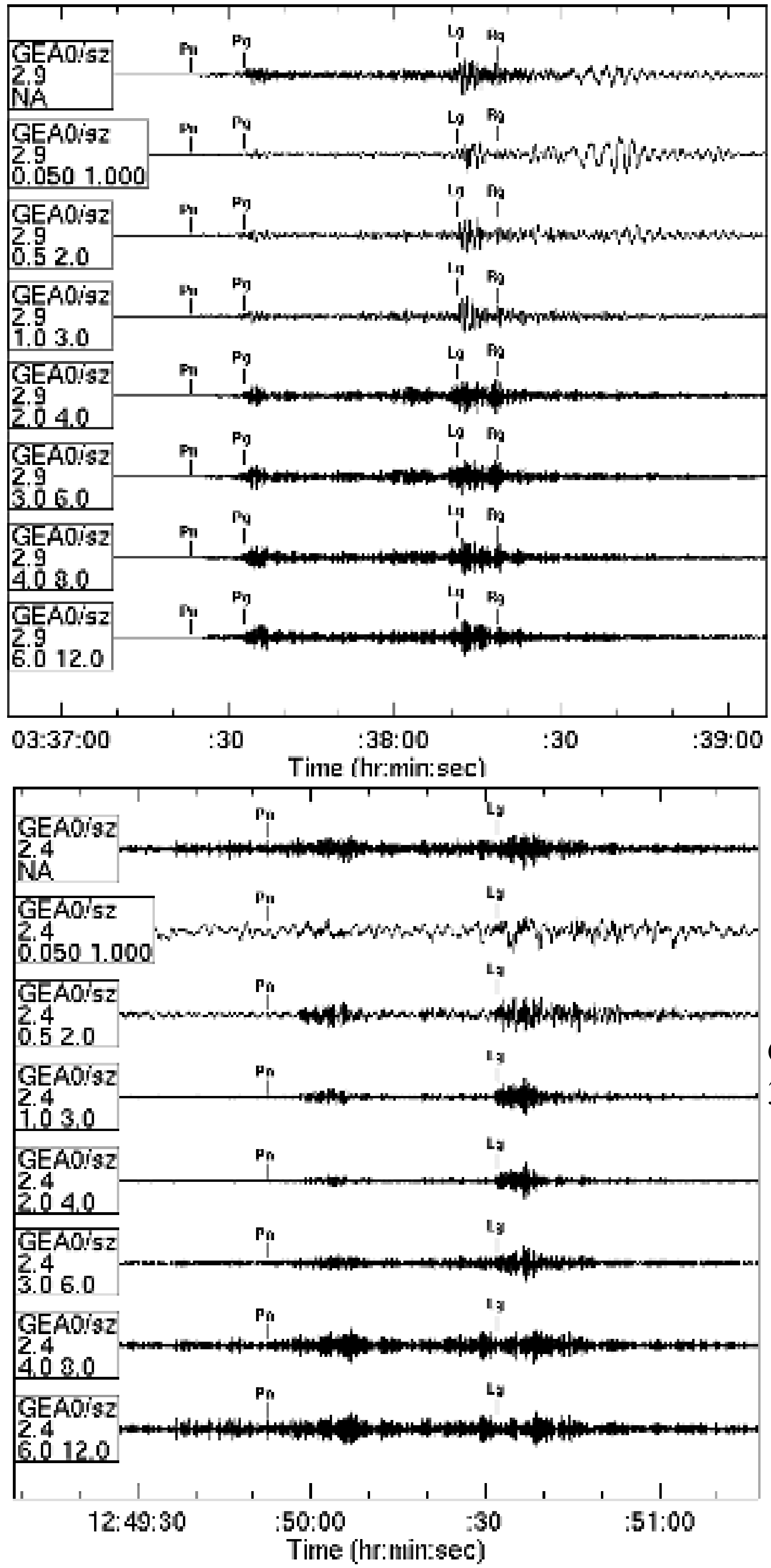


Figure 6. Comparison of LP regional signals (0.03 - 0.10 Hz) at ELK from Utah rockburst, Utah earthquake, NTS nuclear explosion, and southern Nevada earthquake at similar distances (400 - 435 km).



1996/09/11
German Mine
Collapse
4.6 m_b, R = 325 km

1998/01/30
German Mineblast
3.8 m_b, R = 270 km

Figure 7. Comparison of multiple bandpass filter analyses of regional signals at GERES for German mine collapse (top) and German mineblast (bottom) at similar distances.

bands for the different sources. Based on similar comparisons for other European events, we have concluded that there appears to be little distinction in L_g/P_g ratios for European rockbursts and chemical explosions, although the ratios for both source types tend to be larger than those observed for nuclear explosions in other tectonic regions. We are also continuing to look at some of the alternative regional discriminant measures for use in screening these events. In particular, we see in Figure 7 considerable LP Rayleigh wave excitation for the German mine collapse, which is much larger than for the corresponding mineblast; and such LP Rayleigh signals would not be expected from a nuclear explosion. There also appears to be some evidence of more impulsive character in the initial P_n signals from the mineblast for this region compared to the mine collapse, unlike what we saw above in the western U.S. We are analyzing larger event samples for European events with good ground truth recorded at regional IMS stations to evaluate these alternative discriminants.

CONCLUSIONS AND RECOMMENDATIONS

Nominal PIDC/IDC screening procedures almost always fail in rockburst regions. The reason for failure is usually that the IMS station data at teleseismic distances are insufficient for screening relatively small events. There appear to be some systematic differences in several regional signal parametric measurements at IMS stations between rockburst and non-rockburst areas worldwide. Although regional L_g/P ratios at high frequencies are different on average for rockbursts and underground nuclear explosions, there appear to be some anomalies that require explanation and point to utilization of alternative regional observations for more reliable screening of these and other source types. Finally, some issues raised by event screening of mine explosions in Wyoming suggest that there may be need for more careful application of PIDC/IDC screening criteria in some areas and consideration of other regional discriminants for screening.

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